Engineering Research Journal

journal homepage: https://erj.journals.ekb.eg/

Application of phase change materials (PCMs) in administrative building's envelope to improve its thermal comfort

Omnia Abdelghaffar Esmail[1,] *, Mohamed Alaa Mandour[1], Ahmed Halim Hussin[1]

[1] Helwan University - Faculty of Engineering - Department of Architectural Engineering - Egypt

*Corresponding author E-mail: omniaabdo2@gmail.com

Abstract. Renewable energy sources and technologies such as phase change materials (PCMs) have the potential to greatly decrease the ecological footprint of buildings and address the challenges posed by global warming. The integration of PCMs into buildings for thermal energy storage can enhance their thermal efficiency and overall comfort levels, presenting a fresh and forward-thinking solution that resonates with the ongoing emphasis on sustainability and energy conservation in the field of engineering research.

The objective of the study is to propose a strategy utilizing passive cooling techniques in constructing flexible building envelopes to enhance both thermal comfort and energy efficiency in Egypt. This approach involves integrating thermal energy storage materials like phase change materials (PCMs) into building components. By employing PCMs, it becomes possible to regulate thermal loads effectively, resulting in considerable energy savings. The effectiveness of this approach is demonstrated through case studies of buildings where PCMs were utilized, as well as simulations conducted on a hypothetical building situated in Egypt. The simulation study is conducted on an administrative building using DesignBuilder v6.1.0.006 to demonstrate the effect of PCM integration on the building envelope on the thermal comfort and the building energy saving. The simulation results are reported in this work.

Keywords: Phase change materials, thermal comfort, energy efficiency, passive cooling techniques, thermal energy storage (TES).

1 Introduction

The continuing increase in energy consumption in buildings is one of the most pressing issues worldwide. At the global level, the percentage of energy consumed to provide thermal comfort (heating and cooling) reaches 61% of the total energy demand in buildings. According to the International

DOI: 10.21608/erj.2024.333777.1138
Received 12 November 2024; Received in revised form 08 December 2024; Accepted 10 December 2024
Available online 01 March 2025

Energy Agency (IEA), the building sector is most responsible for the growing total energy consumption around the world. [1]

One effective way to create adaptable envelopes is to incorporate thermal energy storage materials, such as phase change materials (PCMs), into their components. Using PCMs, thermal loads can be controlled, resulting in significant energy conservation.

This research paper emphasizes the importance of employing phase change materials in building envelopes as a sustainable solution to address environmental concerns associated with climate change. It primarily studies the properties and capabilities of these materials in enhancing the thermal comfort levels of occupants according to ASHRAE standards, reducing energy consumption, and evaluating the effectiveness of their implementation through analytical examples and applied study as sustainable adaptive systems to meet indoor thermal environmental quality standards.

1.1. Research problem

The research paper problem is that the buildings rely heavily on energy-consuming active mechanical systems to maintain the quality of the indoor thermal environment, rather than incorporating energy-efficient design elements as a result of the limited understanding of the application of latent thermal energy storage technologies (phase change materials) in building envelopes.

1.2. Research objective

The research paper aims to investigate how phase change materials can enhance the thermal efficiency of buildings, and it also intends to monitor and assess the thermal performance of phase change materials incorporated into different components of an administrative building envelope.

1.3. Research Methodology

The research paper followed various methodologies to reach the objectives:

Inductive methodology: the basic concepts and criteria for thermal comfort, thermal energy storage system, the nature of phase change materials, their classification, properties, and ways to integrate them are studied.

Descriptive analytical methodology: a study of the factors affecting the performance of PCM in the building envelope, selection criteria, and their applications in the building envelope was carried out. An analytical study was conducted of several existing buildings that use PCMs and simulate a proposed administrative building that implements and analyzes the results of the simulation through the DesignBuilder v6.1.0.006 program (Fig. 1).

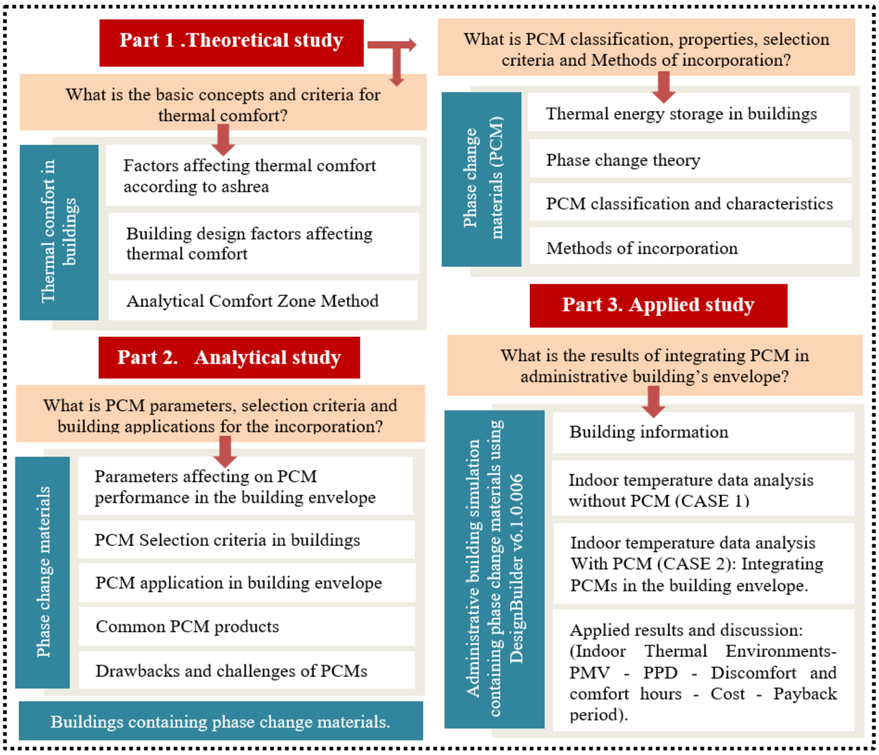


Fig. 1. Visual representation of the research methodology

Theoretical study

2 Thermal comfort in buildings

It refers to the subjective perception of thermal conditions, where individuals feel neither too hot nor too cold and feel a sense of coziness. [2], According to ASHRAE, thermal comfort refers to the psychological state of being satisfied with the temperature conditions in the surrounding environment [3].

2.1. Factors affecting thermal comfort according to ASHRAE.

When establishing thermal comfort standards, six key factors need to be considered. The six factors are divided into environmental factors (air temperature, radiant temperature, relative humidity, and air velocity) and personal factors (metabolic rate (M) and clothing (clo)) [4].

2.2. Building design factors affecting thermal comfort

There are some parameters that can be adopted during the design process to achieve thermal comfort.

Building form. The shape of the building mass affects the amount of energy loss and gain; for example, compact forms are best in climates that require minimal heat gain (such as a hot, dry climate). Fig. 2. shows changing the external surface area by changing the shape of the building (when the size is constant), and the length of the perimeter of form A is 35% greater than that of form B. [5]

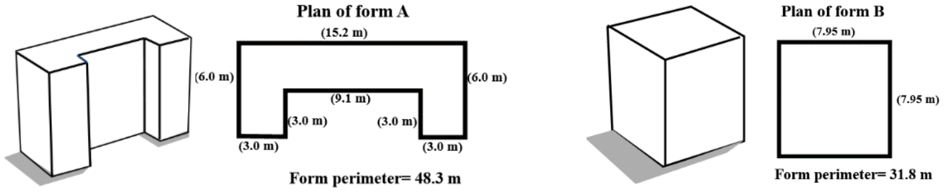


Fig. 2. Changing the external surface area by changing the shape of the building for form A and B. [5]

Wall layers. The wall layers of a building play a key role in regulating temperature and creating a comfortable indoor environment. Insulation materials, Thickness of the wall, Thermal conductivity, Ventilation and air circulation, Solar heat gain, using materials with high heat capacity, and using double walls and roofs to ventilate the building envelope can affect the thermal radiation of the wall. [6] Fig. 3. Shows u-value following different wall layers. A = 4.185 W/m2-K; B = 0.531 W/m2-K; C = 1.59 W/m2-K.

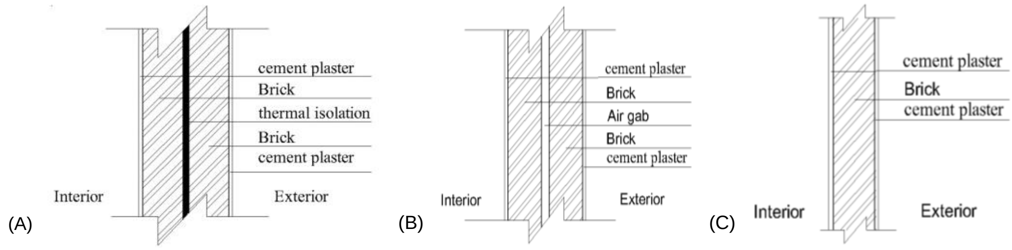


Fig. 3. Different wall layers

Wall finishes. Several factors can influence the thermal properties of wall finishes, including the type and insulation properties of the material used; the color and texture of wall finishes can affect thermal comfort by absorbing or reflecting heat. [7]

Building opening. orientation, size, Proper insulation around windows, Double- or triple-glazed windows with low-emissivity coatings, Using blinds, curtains, or shades can help control the amount of sunlight and heat that enters a room, and reflective window films can also be applied to reduce heat gain in summer. [8]

2.3. Determining Acceptable Thermal Environment in Occupied Space by Analytical Comfort Zone Method

This method uses computer code. Compliance is achieved if $-0.5 < PMV < +0.5$ and $PPD < 10$. [10] Fig. 4 provides graphical examples of the comfort zone using the Analytical Comfort Zone Method.

Predicted mean vote (PMV). An index that predicts the mean value of the thermal sensation votes (self-reported perceptions) of a large group of persons on a sensation. [11]

Predicted percentage of dissatisfied (PPD). An index that establishes a quantitative prediction of the percentage of thermally dissatisfied people determined from PMV. (PPD) index is related to the PMV as defined in (see **Error! Reference source not found.**). [12]

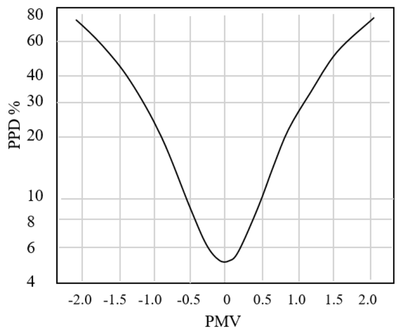


Fig. 5. Predicted percentage dissatisfied (PPD) as a function of predicted mean vote (PMV). [12]

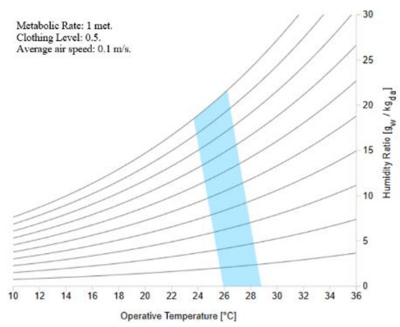


Fig. 4. Predicted percentage dissatisfied (PPD) as a function of predicted mean vote (PMV). [10]

3 Phase change materials (PCMs)

3.1. Thermal energy storage (TES) in buildings

Thermal energy storage (TES) systems combined with buildings have emerged as an effective and promising technology in reducing energy demand. [13]

Latent Heat Storage (LHS): It is an effective way of storing thermal energy and has the advantages of high-energy storage density and its characteristics to store heat at a constant temperature corresponding to the phase-transition temperature of phase change material (PCM). [14] [15]

3.2. Phase change theory

As a material changes phase from a solid to a liquid, it absorbs energy from its surroundings while remaining at a constant or nearly constant temperature. Solidification is the reverse of this process, during which the material transfers energy to its surroundings and the molecules lose energy and order themselves into their solid phase. [16] (See **Error! Reference source not found.**).

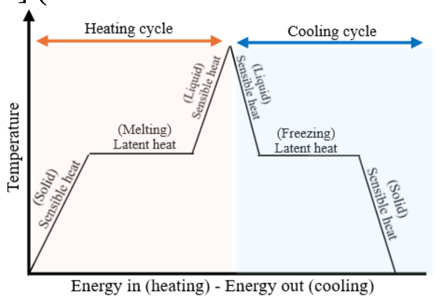


Fig. 6. A simplified temperature graph of the theoretical performance of a PCM [17].

3.3. PCM classification and their availability, cost, and performance characteristics

Organic PCM: They may be *paraffinic:* Paraffin wax is based on slack wax, which is a mixture of oil and waxes. They are widely available and commonly used due to their low cost and proven performance. Or *non-paraffin:* it includes fatty acids and other non-paraffin organics like esters, alcohol, and glycols. Bio-based PCMs are chemically stable and also can last for decades; they are non-toxic and can be cycled through thousands of cycles with no material degradation. They are also gaining traction in the market as sustainable alternatives to traditional PCMs due to fire safety and environmental benefits. On the other hand, they suffer from low thermal conductivity, relatively large volume change, flammability, and non-compatibility with the plastic container. [18] [19]

Inorganic PCM: They are divided into two subgroups called salt hydrates: They are the most widely studied PCMs for the latent heat thermal energy storage system [20]. And metallics: They are basically a combination of low melting point metals and metal eutectics. Inorganic PCMs have a high latent heat of fusion per unit volume, thermal conductivity higher than organic PCMs, are compatible with plastic containers, have a sharp phase change, and have a low environmental impact, potentially recyclable and more available with a lower cost. On the other side, they suffer from subcooling, phase segregation, and incompatibility with metallic containers. [21]

Eutectics PCM: The eutectics are the composition of two or more components, such as organic–organic, organic–inorganic, and inorganic–inorganic. They are not common to use in buildings, have a sharp melting temperature, have a high volumetric thermal storage capability (slightly lower than organic PCMs), have a high cost, and have limited data available on their thermo-physical properties. [22] (See *Table 1*).

Table 1. Latent heat and melting points of some PCMs suitable for cooling in buildings. [23]

	Material	Melting point (C°)	Latent heat (kJ/kg)
organic	1-dodecanol	26	200
	Paraffin C18	28	244
	Methyl palmitate	29	215
Inorganic	$CaCl_2{\cdot}6H_2O$	29	191
	$LiBO_2 \cdot 8H_2O$	25.7	289
	$FeBr_3 \cdot 6H_2O$	21	105
	$LiNO_3 \cdot 3H_2O$	30	296
	KF·4H2O	18.5	281
Eutectics	$C_{14}H_{28}O_2{+}C_{10}H_{20}O_2$	24	147.7
	Methyl stearate + methyl palmitate	23.9	220
	$CaCl_2{\cdot}6H_2O$	29	191
	$LiBO_2{\cdot}8H_2O$	25.7	289

3.4. Methods of incorporation

PCM is combined with the building materials in different methods (direct incorporation, immersion, shape-stabilized, and encapsulation). [18]

Direct incorporation: In this method The PCM in powder or liquid form is added directly to the construction materials during preparation, such as concrete, mortar, or gypsum. [26]

Immersion: In the immersion technique, porous construction elements (concrete blocks, gypsum wallboard, porous aggregate, timber, etc.) are immersed in a container that is filled with a liquid PCM. (See **Error! Reference source not found.**). [25]

Shape-stabilized PCMs: Where the PCM in its molten phase is retained by another material, generally porous, by capillarity, thus, shape-stabilization depends largely on the porosity of the support (see **Error! Reference source not found.**). [27].

Encapsulation: It is performed by covering the PCM with a shell for protection from the outside environment as well as for leakage prevention [29]. There are two main forms of encapsulation: microencapsulation, which consists of placing a small molecular mass in small particles coated with high-performance polymers (see Fig. 9), and macroencapsulation, which is based on the introduction of PCM into tubes, panels, or other large containers. [18] (See **Error! Reference source not found.**).

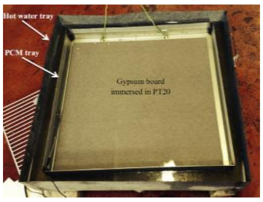


Fig. 7. Immersion of PCM into gypsum board. [25]

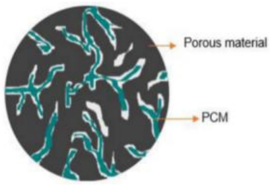


Fig. 8. Shape-stabilized PCM (porous). [28]

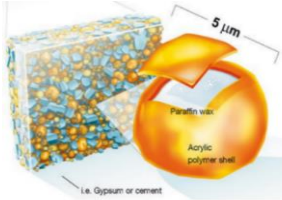


Fig. 9. Micro encapsulated PCM [18]

Fig. 10. Wall PCM macrocapsules [30]

3.5. Influential parameters affecting PCM performance in the building envelope:

The efficiency of PCM in regulating temperature is influenced by various factors that impact its effectiveness. [29]

Melting temperature: The melting temperature refers to the specific temperature at which a phase change material (PCM) transitions from a solid to a liquid state. [30] For human comfort applications, the optimal PCM melting temperature lies between 22–28°C [31].

PCM quantity/thickness: the amount of PCM incorporated into building materials should be evaluated to be the largest possible [18].

PCM position: The best placement might be influenced by many parameters such as climate and weather conditions, application target, indoor environment, thermal properties of wall materials, orientation, and the incident solar radiation, PCMs properties, and PCMs' quantity (See **Error! Reference source not found.**). [24].

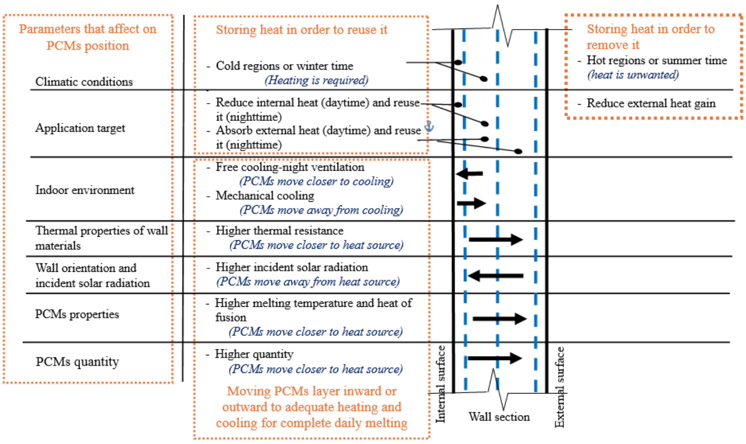


Fig. 11. A summary of the optimum position of the PCM's application in building walls, based on several influential parameters. [24]

3.6. PCM Selection criteria in buildings

Selection criteria of the PCM specifically for building applications depend on several factors related to the architecture of the building that need to be considered.

Region climate: In hot climates, buildings with proper orientation can benefit from PCM types with high melting points. On the other hand, in cold climates, buildings with different orientations may require PCMs with lower melting.[32] (fig.12) shows that the effectiveness of PCM 23 in Cairo is superior to that in Aswan due to the higher temperatures experienced in Aswan.

Building glazing: Buildings with large windows may experience greater solar heat gain. In such cases, high-melting-point PCMs with higher thermal storage capacities may be more effective. Conversely, buildings with limited windows may require lower-melting-point PCMs. [33] (See **Error! Reference source not found.**).

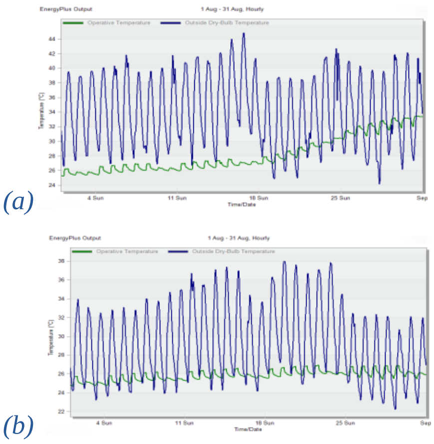


Fig. 12. Simulation results of two room with PCM 23 (a) in Aswan, (b) in Cairo.

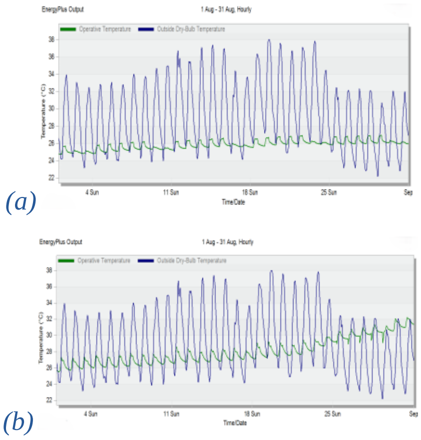


Fig. 13. Simulation results of two room with PCM 23 (a) with small window, (b) with large window in August

Building shape: Compact building shapes with reduced S/V ratio (surface area to volume ratios) can enhance the effectiveness of PCMs by minimizing heat loss or gain through the building envelope (See **Error! Reference source not found.**). [34]

Integration with building materials: PCM should be integrated with the insulation system of the building to optimize thermal performance and enhance the efficiency of PCM in storing and releasing heat (see **Error! Reference source not found.**). 36]

Night ventilation and airflow: Night ventilation can help pre-cool PCM during cooler nighttime temperatures, allowing it to store more thermal energy for use during the day. Proper airflow can ensure efficient heat transfer between PCM and the surrounding space. [35][37]

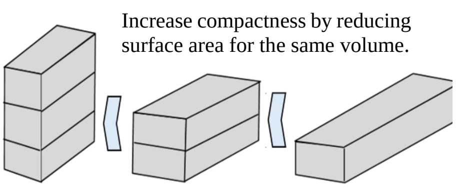


Fig. 14. Minimize S/V ratio [41]

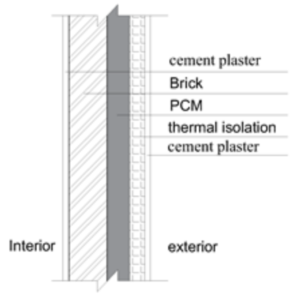


Fig. 15. Wall section integrated with PCM and thermal insulation.

Analytical study

3.7. PCM application in building envelope for passive systems

The integration of PCMs passively into building walls, roofs, and floors can potentially increase the thermal mass of these components, decrease heat transfer rates during peak hours, and reduce the interior temperature fluctuations. [22]

Wallboards and panels: They are very suitable for the incorporation of encapsulated PCMs and can be produced in mass quantities in a controlled environment at the factories, which reduces the waste materials and provides higher quality control. PCM is integrated with wallboard and installed in place of ordinary wallboards during construction or refurbishment. [37]. (See **Error! Reference source not found.**).

Cement mortar/plaster/concrete mixture: (PCMs) are commonly incorporated into construction materials by blending them directly with cement mortar, gypsum, and concrete. [39]

Bricks and blocks: The incorporation might be done by macroencapsulated PCMs-bricks were produced by filling the PCM into the cavity of the bricks. (See **Error! Reference source not found.**.) PCM macro-capsules made of steel were incorporated into brick masonry walls, and shape-stabilized PCMs were incorporated into cement mortar to produce PCM bricks. [41]

Windows: These windows usually consist of a single or multilayer glazing panel made of conventional glass, integrated with a layer of a transparent or translucent PCM. (See **Error! Reference source not found.**) [13]

Fig. 16. Two-layer integration of PCM boxes in wall. [38]

Fig. 17. Integration of PCM in hollow brick. [40]

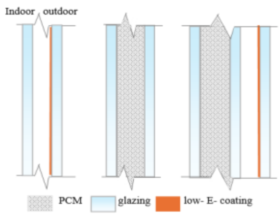


Fig. 18. PCM integrated in window glass [43]

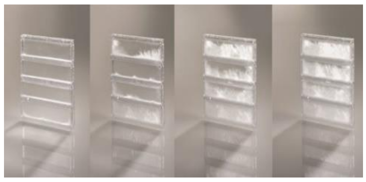


Fig. 19. PCM-enhanced window component with variable optical properties [42]

Roofs: Integrating PCMs into roof structures helps in controlling building heat transfer more effectively, providing substantial thermal inertia. This integration decreases the transfer of changing heat loads and enhances the energy efficiency of the building. (See **Error! Reference source not found.**). [37]

Floors: Floorboards, tiles, or panels can be enhanced with PCM. The application may vary widely, like a single-layer PCM application on the floor or multi-layer with different types of PCM. (See **Error! Reference source not found.**). [39]

Ceilings: PCM cooling applications in ceilings are either passive (similar to PCM-enhanced wall gypsum boards or internal plasters) or active. (See **Error! Reference source not found.**). [44]

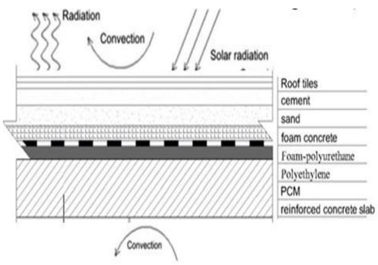


Fig. 20. Composition of a roof with PCM. [37]

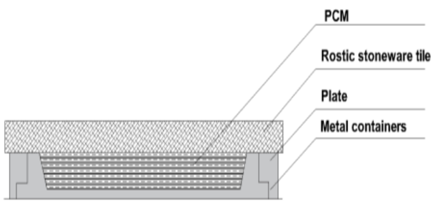


Fig. 21. PCM integrated in floor tiles. [39]

Fig. 22. PCM integrated in ceiling [44]

3.8. Common PCM products for building applications and their manufacturers

- **Weber.Mur Clima®:** dry gypsum plaster mix is manufactured in Germany by Saint Gobain Weber. This preformulated product is recommended for interior plaster applications. It contains microencapsulated PCM for passive temperature control, mineral lightweight aggregates, chemical additives, and adhesives for better workability and easier site application.
- **Knauf PCM Smartboard®:** It is the interior plasterboard product manufactured by Knauf, Germany. It is commercially available for drywall construction applications with around 30% mass fraction of microencapsulated paraffinic PCM manufactured by BASF.
- **ThermaCool® Wallboards and Mineral Ceiling Tiles:** Datum Phase Change Ltd. is a UK manufacturer specializing in incorporating PCM into building products under the brand name ThermaCool®. It contains microencapsulated organic PCM of melting point at 23 °C.
- **CoolZone—PCM-Enhanced Metal Ceiling Tiles:** Manufactured by Armstrong, UK, it is based on conventional unperforated metal ceiling tiles with the addition of the 24-mm-thick dynamic thermal core containing about 25% by weight of the microencapsulated PCM with a melting temperature of 23°C.
- **BioPCmat™—Foil-Based Array of PCM Containers:** by Phase Change Energy Solutions of Asheboro, NC, USA, BioPCmat™ is the trade name for a family of proprietary bio-based PCMs. Based on different PCM loads.
- **GLASSX Façade System: GLASSX Inc.** of Zurich, Switzerland, developed a translucent glass façade system. This technology is based on a thin layer of translucent PCM packed into 16-mm-thick transparent plastic containers.

3.9. Drawbacks and challenges of using PCMs in buildings

A significant drawback of using phase change materials (PCMs) in construction is the difficulty of maintaining the PCM system when the PCM loses its effectiveness after 1000 freeze/melt cycles.

PCMs challenges:

- **Supercooling Effects:** Supercooling is defined as the state where a liquid solidifies below its normal freezing point and hence experiences a delay in starting its solidification process. Adding a nucleating agent can help reduce the effect of supercooling. By promoting the formation of crystals at the intended freezing point, the nucleating agent helps prevent the liquid from remaining in a supercooled state for an extended period of time.
- **Low thermal conductivities:** these can restrict PCMs' potential in thermal energy storage systems by slowing down the rate at which heat is absorbed and released during the solid-liquid phase transition. Adding fins to the heat exchanger area or creating new PCM composites with additives to boost thermal performance are two ways to improve the low thermal conductivities of PCMs.
- ***Phase segregation:*** In order to minimize any negative consequences, this problem must be resolved by using thickening and nucleating agents in PCM applications. This aids in preserving PCMs' efficacy and efficiency in a range of thermal management systems.
- **Fire Safety of PCMs:** Paraffin transforms into a vapor during a fire, which is likely to be ignited by the fire's high temperatures and raise a building's fire load. Using fire retardants can reduce the detrimental effects of fire. [9]

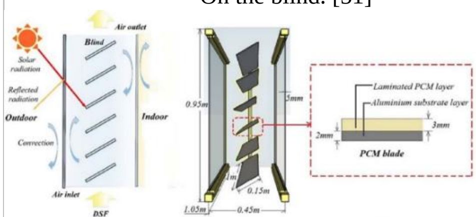
4 Analytical study of buildings containing phase change materials

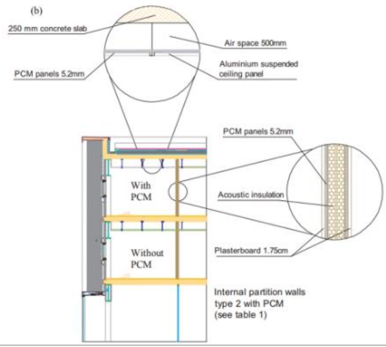
The research adopted an analytical descriptive method, with the intention of presenting a precise depiction of the phenomena under investigation.

Criteria for selecting study samples:

- Ensuring a diverse range of applications for phase change materials in building envelopes, such as walls, ceilings, and blinds.
- Considering geographical and climatic diversity among the buildings chosen for the study.
- Taking into account the varied purposes of the buildings, including administrative, educational, medical, residential, and sports facilities.

Table 2. Presented the analytical study of building containing PCMs.

Table (2)	**Coventry University, John Laing Building**	**Miramar Bank**
Building classification	educational	Administrative
Building location	Miramar, Florida, USA (Temperate)	Much Park St, Coventry, UK. (Temperate)
PCM location	The PCM Tube modules were installed behind ceiling tiles [45] [46]. 	ENRG Blankets® PCM sheets were installed behind ceiling tiles [48]. 
PCM classification	Inorganic (Salt Hydrate PCM) [45].	Organic (Bio PCM). [49]
Methods of incorporation	(Encapsulation) TubeICE containers are supplied as fully sealed, PCM-filled HDPE tubes. The tubular design enables them to be stacked effectively in both rectangular and cylindrical tanks with minimal void space [47]. 	(Encapsulation) BioPCM® family of formulations between two rugged, multi-layer films (polymer and/or aluminum) [49]. 
Melting temperature (C°)	27 [47]	23° [49]
PCM quantity/thickness	1m x 2″ [45]	24” x 48”- 2,720 sq. ft [49]
The impact of the use of materials in the building	1. The temperature fluctuations reduced, and the room's thermal performance improved. 2. They help maintain the internal conditions of buildings to a thermally comfortable range. Therefore, the students' complaints about the high temperature stopped. 3. The temperature decreased from 36.4° to 32°C and 31°C. 4. The energy needed for heating and air-conditioning reduced. 5. Reduces CO2 emissions because of the lack of reliance on mechanical devices.	1. The temperature fluctuations reduced, and the building thermal performance improved. 2. The BioPCM® enables active heat absorption in the ENRG Blanket® and delays the need for cooling in summer. Similarly, in winter, the ENRG Blanket® can be tuned to absorb and release stored heat when room temperature drops below the desired set point. 3. Avoided carbon dioxide emissions by 20 metric tons/year. 4. The building HVAC energy savings by 23%. 5. The temperature decreased, so the HVAC demand reduced.
	Easton Archery Center	**CSET building**
Building classification	sports	Administrative - educational
Building location	Chula Vista, California (Arid)	Ningbo, China (Temperate)
PCM location	Interior and exterior walls below the roof sheeting. [50] 	On the blind. [51] 
PCM classification	organic (bio-based material) [50]	organic PCM
Methods of incorporation	(Encapsulation) BioPCM® family of formulations between two rugged, multi-layer films (polymer and/or aluminum). [49]	(Encapsulation) Laminated composite micro-encapsulated PCM blade [44].
Melting temperature (C°)	23° [49]	35°C [52]
PCM quantity/thickness	24"x48" - 140,000 sq. ft. [50]	3 mm [52]
The impact of the use of materials in the building	1. Reduces CO2 emissions Because of the lack of reliance on mechanical devices.	1. Reduces CO2 emissions Because of the lack of reliance on mechanical devices. 2. PCM caused energy savings because of the natural ventilation system in the DSF.

	2. The building doesn't depend on mechanical cooling, so the energy needed for heating and air-conditioning is reduced. 3. This provided the thermal mass required to control temperature. 4. The BioPCM® maintains thermal comfort inside the structure. 5. The temperature fluctuations reduced, and the building thermal performance improved.	3. The air temperature at different positions in the DSF test cell did not exceed 39°C during the daytime. 4. The daytime average cavity air temperature became below 35 °C. 5. The air temperature of the internal glass decreased, which caused a decrease in the temperature of the internal spaces behind the glass, causing the thermal comfort.
	University of Maryland Medical Center [UMMC]	**University Campus of the city of Aveiro**
Building classification	medical	residential
Building location	Baltimore, Maryland, United States (Temperate)	Aveiro city, North Portugal (Mediterranean)
PCM location	On top of the ceiling tiles [53]. 	Above the ceiling tiles and in the interior side of the partition wall [54]. 
PCM classification	Inorganic	Organic (BioPCM®)
Methods of incorporation	(Encapsulation) Templok sheets of mineral PCM. Panel material: thermoplastic 20 mil top/Bot, foil lined top [53].	(Encapsulation) micro-encapsulated PCM panels [54].
Melting temperature (C°)	23˚C	23˚C
PCM quantity/thickness	2'x4'- 70% of the space [53]	2.1 mm in thickness [54]
The impact of the use of materials in the building	1. Reduces CO_2 emissions Because of the lack of reliance on mechanical devices. 2. PCM caused energy savings are likely to be 1,500 to 2,000 KWH per month. 3. This provided the thermal mass required to control temperature and made it in limits of 23°C. 4. The hot/cold calls have reduced to zero due to the thermal comfort. 5. The temperature fluctuations reduced, and the building thermal performance improved.	1. Reduces CO_2 emissions Because of the lack of reliance on mechanical devices. 2. PCM caused energy savings because of the natural ventilation system. 3. A reduction of discomfort for the heating season of 2.61% was measured for the room with PCM (41.47% in discomfort) when compared with the same period for the room without PCM (44.55%). 4. The temperature fluctuations reduced, and the building thermal performance improved because the overheating rate during the summer season decreases about 90%.

Applied study

5 Administrative building simulation containing phase change materials using DesignBuilder v6.1.0.006

5.1. Building information

The research seeks to analyze a hypothetical design of a compact administrative building (bank) that utilizes phase change materials in its envelope to enhance thermal comfort. This will be accomplished by utilizing the DesignBuilder v6.1.0.006 program to simulate the proposed building. (See **Error! Reference source not found.**), the building is situated in Cairo, Egypt. The temperature fluctuates between 5.8°C and 44°C. The structure utilizes night ventilation and comprises a single story with a total area of 412.8 m². The floor height ranges from 3.7 m to 4.7 m.

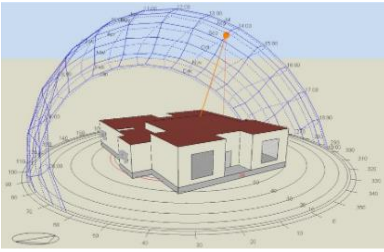


Fig. 23. Perspective of the building model

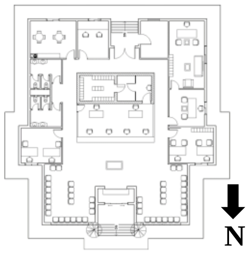


Fig. 24. Building's plan

Building components and materials: *Tables 3 and 4* show the building construction materials of the walls, roof, and floor and window details. (See Fig. 25)

Activity profile: The occupancy density (15/100 m2 for banks) according to ANSI/ASHRAE Standard 62.1-2016.The activity is typing, the metabolic rate is 1.1 met and the average air speed is 0.137 m/s. The clothing is set in winter to be 1 and summer 0.5 with led lighting power density of 5.38 (w/m2).

Building modeling on DesignBuilder v6.1.0.006 program: The simulations conducted primarily involve creating a model of the building, using the same materials as mentioned earlier, to estimate its thermal load. To evaluate the indoor thermal comfort, the CBE Thermal Comfort Tool was employed.

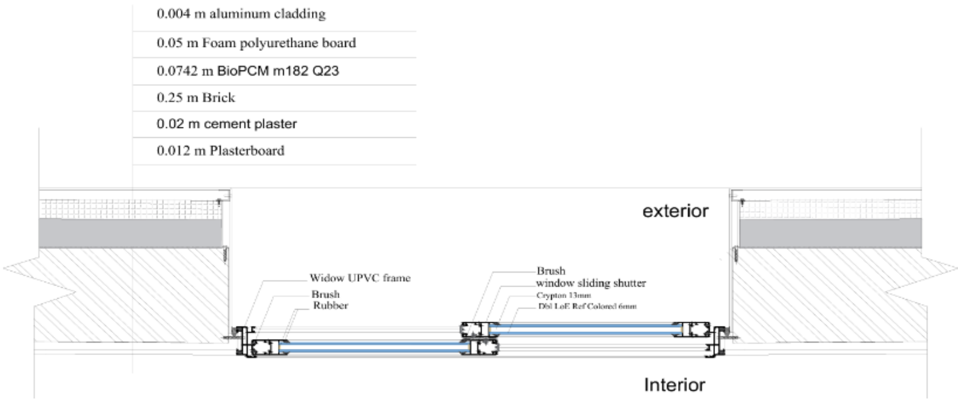
Table 3. Building materials

	With PCM (case 2)	Thickness	Conductivity	R-Value (m^2-k/w)
Eternal wall	(exterior) Metal cladding	0.004	0.29	1.162
	Foam – polyurethane board	0.05	0.023	
	bioPCM m182 Q23	0.0742	0.2	
	Brick	0.25	0.72	
	Cement plaster	0.02	0.72	
	Plasterboard	0.012	0.25	
Roof	(exterior) cement tile	0.02	1.5	2.15
	Cement mortar	0.02	0.72	
	Sand	0.07	1.74	
	Foam concrete	0.07	0.08	
	bioPCM m182 Q25	0.0742	0.2	
	Foam-polyurethane board	0.05	0.023	
	Polyethylene	0.006	0.33	
	Reinforced Concrete	0.2	2.5	
	Cavity layer (R = 0.18 m²-K/W)	0.4	-	
	bioPCM m182 Q23	0.0742	0.2	
	Perforated aluminum ceiling	0.0005	230	
Floor	marble tiles	0.02	3.5	0.22
	Cement mortar	0.02	0.72	
	bioPCM m182 Q23	0.0742	0.2	
	Sand	0.06	1.74	
	Concrete	0.10	1.7	
	Bitumen felt/sheet	0.006	0.23	
	Concrete	0.15	1.7	

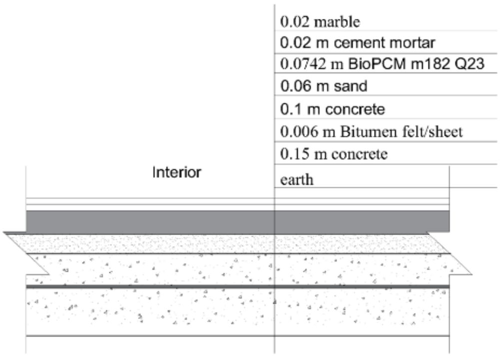
Table 4. Windows details

Glazing type	Dbl LoE Elec Ref Colored
layers	Thickness (mm)
Generic ECREF-2 COLORED	6

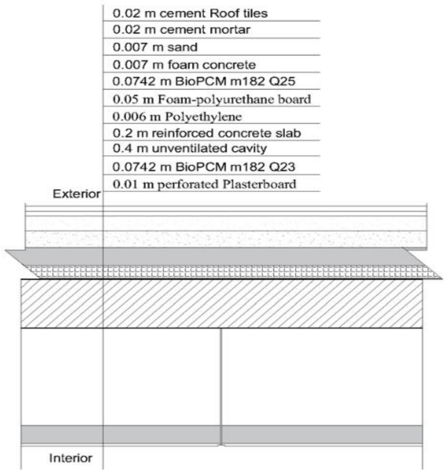
KRYPTON	13
Generic LoE SPEC SEL CLEAR-Rev	6
U-value	1.228 W/m²-k
frame	UPVC
Inside Shade	Blind with high reflectivity slats



(a) Plan of External Wall and Window



(b) Section of Ground Floor



(c) Section of Roof

Fig. 25. Sections of the building envelope with PCM.

5.2. Indoor temperature data analysis without PCM (CASE 1)

The average temperature levels per hour were recorded in two simulations before integrating the Phase Change Material (PCM) across two seasons (summer, winter).

5.3. Indoor temperature data analysis with PCM (CASE 2)

Integrating PCMs in the building wall, roof, and floor: After conducting numerous simulation tests, it was determined that the most suitable approach is to incorporate two layers of PCM with a melting temperature of 23° and 25° C into the roof and one layer of 23° C in the east, west, and south walls, as well as the floor.

Selection of PCM: BioPCM® is highly tunable, non-corrosive, non-toxic, non-combustible, recyclable, and eco-friendly. In this work, BioPCMs M182/Q23 and Q25 (indicated as PCM 23 and 25) are used in the simulations. The main characteristics of this type of PCM are listed in *Table 5* [55]. For all simulations, a PCM layer with a thickness of 0.0742 m is embedded in the walls, roof, and floor.

Table 5. Thermophysical properties of BioPCMs M182. [55]

Property (unit)	value
Density (kg/m³)	950
Specific heat capacity (J/kg K)	2200
Thermal conductivity (W/m K)	0.2
cost	35 $ per m^2

5.4. simulation results' discussion:

Based on the data collected from the simulations, it appears that:

- **Indoor Thermal Environments:** Incorporating phase change materials (PCM) in a building's envelope leads to higher temperatures in winter and lower temperatures in summer that create a more favorable thermal environment for occupants. Simulation results demonstrate that the temperature inside the building in *winter* changes from a range of (19.1°C : 24.7°C) to a range of (22.5°C : 24.6°C); it increased by 3.4°C, and the humidity ratio increased from (25.9% : 93.2%) to (26.2% : 73.1%). In *summer*, the operative temperature is altered from a range of (26°C : 34.5°C) to a range of (23.7°C : 25.9°C); it decreased by 8.6°C when using phase change materials, and the humidity ratio changed from (29% : 98.3%) to (54.4% : 100%). (See Figs. 26, 27).

Fig. 26. Indoor temperature data analyzed in winter (with and without PCM)

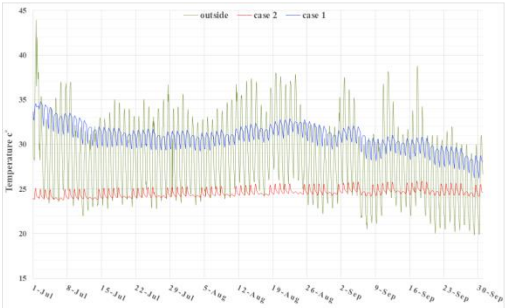


Fig. 27. Indoor temperature data analyzed in summer (with and without PCM)

- **Determining the Acceptable Thermal Environment in Occupied Space for Case 2:** Analytical Comfort Zone Method was used to determine the range of temperatures in which all the occupants will find thermal comfort using relative humidity, air speed, clothing level, and the highest and lowest metabolic rates in winter and summer. It appears that the temperature range is between 20.1˚C and 25.6˚C in winter and between 20.1°C and 27.2°C in summer. Determining if the specific temperature is comfortable or not depends on the relative humidity of its temperature. See Figs. 28, 29.

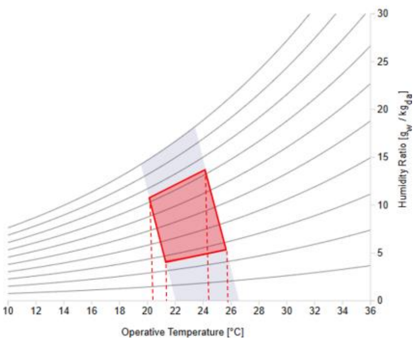


Fig. 28 .The comfortable temperature range in winter

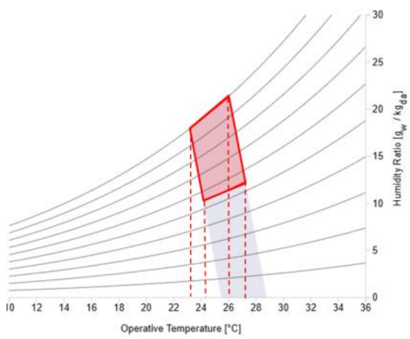


Fig. 29 .The comfortable temperature range in summer

Predicted Mean Vote (PMV): For *case 1*, the PMV values ranged from -0.89 to 3.6, which is outside the acceptable range of -0.5 to +0.5. This indicates that a significant portion of the data did not meet the criteria for thermal comfort outlined by ASHRAE standards. On the other hand, for *case 2*, the PMV values ranged from -0.49 to 0.57, which is relatively close to the acceptable range (see Fig. 30).

Predicted Percentage Dissatisfied (PPD): For *case 1*, PPD values ranged from 5% to 100%, which is outside the acceptable range. On the other hand, for *case 2*, PPD values ranged from 5% to 11.7%, which is relatively close to the acceptable range (see Fig. 31).

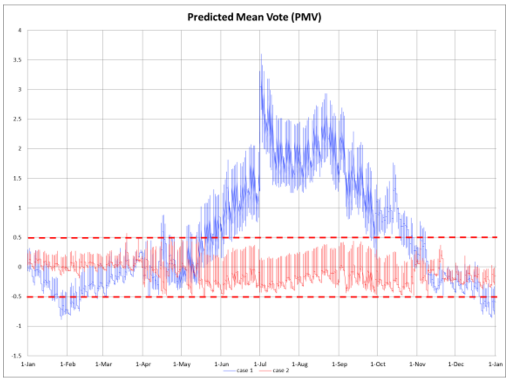


Fig. 30. (PMV) over the year for cases 1 and 2.

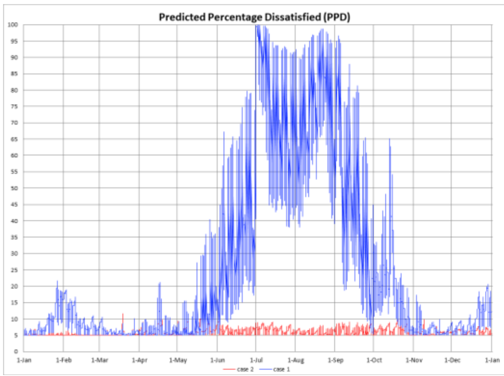


Fig. 31. (PPD) over the year for cases 1 and 2.

- **Discomfort and comfort hours:** Discomfort and comfort hours were calculated via DesignBuilder and CBE Thermal Comfort Tool in various directions throughout the entire duration and during the occupied period between 8 am and 4 pm. By utilizing PCM, the number of uncomfortable hours throughout the year was reduced to just 2 hours (*Tables 6 and 7).* Display the total hours and the hours of discomfort and comfort experienced throughout each season and during the occupied period of each season within a given year.

Table 6. Comfort and discomfort hours in winter.

season	winter			
case	Case 1		Case 2	
period	All	occupied	All	occupied
Total hours	2160	512	2160	512
Discomfort hours	455	61	2	2
Comfort hours	1705	451	2158	510

Table 7. Comfort and discomfort hours in summer.

season	summer			
case	Case 1		Case 2	
period	All	occupied	All	occupied
Total hours	2208	528	2208	528
Discomfort hours	2190	528	0	0
Comfort hours	18	0	2208	528

- **Cost:** The initial cost of installing PCM panels or materials may be higher compared to traditional insulation methods. Over time, the energy savings from reduced heating and cooling needs can offset the initial cost, leading to long-term cost savings for building owners.

  Payback period: An economic evaluation was conducted to determine the simple payback duration of PCM technology. The average cost of installing an air conditioning system is 1,442,000 pounds (7 concealed air conditioners with a capacity of 7.5 HP; each price is 206,000 pounds). A 5-ton air conditioning unit consumes approximately 7 kWh, so the annual consumption value is

102,312 kWh. Energy prices in commercial buildings in Egypt in 2024 are equal to 1.80 Egyptian pounds per kilowatt-hour. Thus, the annual energy consumption cost amounts to 184,161.6 pounds.

Table 8. PCM cost and payback

	Cost (LE)	PCM Payback period
BIOPCM M182 Q23, Q25	3,027,912	8.6 years.
Air conditioning system	1,442,000	
Annual energy consumption	184,161.6	

The simple payback of PCM is calculated by subtracting the air conditioning system installation expenses from the overall PCM costs and then dividing the outcome by the annual energy consumption cost in Egyptian currency, and then the payback will be 8.6 years. See *table 8*.

5.5. Applied study results:

- The consideration of the building's architecture factors Region climate, glazing, shape, materials of the building, and the ventilation system led to the best choice of the PCM.
- The findings indicate that using BioPCMs M182/Q23 and Q25 is suitable for Cairo's climate.
- Using limited windows in the east, west, and south elevations requires lower-melting-point PCMs to effectively store and release thermal energy.
- The compact shape of the building decreased the amount of heat absorbed by the building envelope, which is beneficial for containing and optimizing the PCM's performance.
- Using thermal insulation helps maintain a stable temperature within the building and enhances the efficiency of PCM in storing and releasing heat.
- Integrating night ventilation in the building enhanced the effectiveness of PCM by providing opportunities for natural cooling and heat dissipation.
- The PCM system helped regulate temperature and save energy as well as increase the overall value of the building by reducing the need for air conditioning systems.
- Using phase change materials resulted in an increase of 17.8% in operative temperature during the winter season, while there was a 24.9% decrease during the summer season.

6 Results

- The DesignBuilder program is used to simulate the effect of adding PCMs materials in building envelope in Egypt.
- Improving human comfort through elements such as general design, function, occupants, location, and cooling and heating systems is the main goal of building design.
- **Understanding PCM types**: Organic PCMs are highly versatile and advantageous compared to other types, but integrating them effectively requires additives to address any shortcomings.
- **The ability of incorporating PCMs in building envelopes**: Ability to integrate PCMs into the building envelope: Materials can be integrated into the walls, ceilings, and floors of a building. The method of integrating PCMs must be tailored to the type of material, its intended application in the building, and cost considerations.
- **Thermal comfort improvements in buildings**: - It can easily be influenced by the boundary conditions, the type of PCM, the melting temperature, the PCM quantity, the PCM position, the orientation of the building, and the components of the building.
  - The building's shape and configuration affect how energy is exchanged.
  - Building openings and wall finishes, as well as the kind and insulating material properties, can all affect thermal comfort.
  - The phase change temperature of PCMs should be between 22°C and 28°C so it can meet thermal comfort criteria.

- PCM systems help regulate the building's operative temperature within a specific range.
- PCMs contribute to a comfortable indoor environment by managing peak temperatures and offering a more evenly distributed thermal atmosphere, resulting in enhanced comfort and reduced thermal discomfort for occupants.

- **Energy savings:** It is achieved through natural ventilation and reduced reliance on mechanical heating and cooling systems due to PCM incorporation in buildings.
  - The use of PCMs can also extend the lifespan of HVAC systems by reducing their workload, thereby decreasing maintenance and replacement costs.
  - Utilizing phase change materials (PCMs) can also prolong the durability of HVAC systems by lessening their burden, thus leading to lower maintenance and replacement expenses.
  - Increased thermal inertia from PCM leads to minimized temperature fluctuations, ensuring more stable indoor temperatures and improved thermal efficiency.
- **The use of phase change materials in achieving thermal comfort without relying on air conditioning devices can indeed have several benefits leading to improving sustainability in buildings:**
  - Maintaining air purity by not burning fossil fuels and reducing greenhouse gas emissions, which helps in reducing the phenomenon of global warming.
  - Reducing energy consumption and pressure on electricity networks. By shifting away from traditional air conditioning systems, we can lower the demand for electricity, which can help in reducing strain on the energy grid.
  - Reducing stress on the energy infrastructure that causes power outages or voltage fluctuations. By lowering energy demand for cooling, we can help in stabilizing the energy grid and preventing potential disruptions.
  - Reducing health problems caused by recycled air from air conditioners. By relying less on air conditioning systems that circulate indoor air, we can potentially lower the risk of health issues associated with poor indoor air quality.

7 Conclusion:

This paper explores the potential of phase change materials in various applications, including walls, ceilings, floors, and windows. The use of phase change materials in building envelopes is a cutting-edge approach in sustainable architecture and green building practices.

By incorporating these materials into building envelopes, they enhance thermal comfort and energy efficiency. This approach also helps reduce environmental pollution, the stress on the energy infrastructure, the pressure on water resources, and the health problems caused by cooling and heating systems by reducing reliance on them. The research includes evaluating the thermal effectiveness of phase change materials in a proposed administrative building and evaluating the impact of their inclusion in such envelope.

8 Recommendations

1. **Understanding the building's thermal needs :**before selecting and installing phase change materials (PCMs), it's essential to understand the thermal requirements of the building.
2. **Monitoring and Maintenance:** Regular monitoring and maintenance of PCM systems are necessary to ensure their continued effectiveness.
3. **Consider Local Climate:** The local climate should also be taken into account when applying PCMs in buildings. Different climates may require different types or configurations of PCMs to achieve optimal performance.
4. **Choosing the Right PCM:** Selecting the right PCM is crucial for effective thermal energy storage and taking into account some factors such as the melting point of the PCM, its compatibility with

building materials, thermal conductivity, latent heat capacity, chemical stability, and cost-effectiveness.

5. Pushing scientific research towards creating advanced passive adaptation materials to achieve environmental compatibility with current and future variables.
6. Supporting research on the applications of phase change materials in buildings, especially that research that deals with the combination of thermal insulation materials and phase change materials in building envelopes because of their great effectiveness in reducing energy demand for cooling purposes in hot, dry environments.
7. For the department of Energy: Oversee energy efficiency initiatives and provide funding for research on PCMs.

References

[1]. International Energy Agency (IEA). [cited accessed 2023; Available from: https://www.iea.org/Chow, D.H., Indoor environmental quality

[2]. Chow, D.H., Indoor environmental quality: thermal comfort. 2022.

[3]. عزت محمد وهب, أ.ع.م.و., et al., تحديد مادة العزل الحراري المثلي من ناحية الراحة الحرارية واستهلاك الطاقة في دور السطح باستخدام برنامج المحاكاة البيئية Design Builder. Engineering Research Journal-Faculty of Engineering (Shoubra), 2021. **50**(1): p. 197-211.

[4]. Permana, A.S. and S. As' ad, Progress in Sustainable Development. 2023: Elsevier.

[5]. Saleem, Y. and S. Mahmood, Application of the Environmental Design Treatments in the Steps of Design Process, in Hot–Dry Climate. Iraqi Journal of Architecture and Planning, 2016. 15(1): p. 19-34.

[6]. Thermal Comfort - Factors affecting thermal comfort in building design. accessed 2024]; Available from: https://www.wbdg.org/design-objectives/productive/provide-comfortable-environments.

[7]. ASHRAE. accessed 2024]; Available from: https://www.ashrae.org/.

[8]. Almarzouq, A. and A. Sakhrieh, Effects of glazing design and infiltration rate on energy consumption and thermal comfort in residential buildings. Thermal science, 2019. 23(5 Part B): p. 2951-2960.

[9]. Bland, A., Khzouz, M., Statheros, T., and Gkanas, E. I., PCMs for Residential Building Applications: A Short Review Focused on Disadvantages and Proposals for Future Development. Buildings, 2017. 7(3), 78.

[10]. ASHRAE, ANSI/ASHRAE Standard 55-Thermal environmental conditions for human occupancy, in American Society of Heating, Refrigerating and Air-Conditioning Engineers. 2020.

[11]. Dyvia, H. and C. Arif. Analysis of thermal comfort with predicted mean vote (PMV) index using artificial neural network. in IOP Conference Series: Earth and Environmental Science. 2021. IOP Publishing.

[12]. Fabbri, K., Thermal Comfort Perception: A Questionnaire Approach Focusing on Children. 2024: Springer Nature.

[13]. Faraj, K., et al., A review on phase change materials for thermal energy storage in buildings: Heating and hybrid applications. Journal of Energy Storage, 2021. **33**: p. 101913.

[14]. Delgado, J.M., et al., Thermal energy storage with phase change materials: A literature review of applications for buildings materials. 2018.

[15]. Amer, A.E.A. and V. Lebedev, Thermal energy storage by using latent heat storage materials. vol, 2018. **9**: p. 1442-1447.

[16]. Fleischer, A.S., Thermal energy storage using phase change materials: fundamentals and applications. 2015: Springer.

[17]. Sutterlin, W., Phase change materials, a brief comparison of ice packs, salts, paraffins, and vegetable-derived phase change materials. Pharmaceutical outsourcing, 2011.

[18]. da Cunha, S.R.L. and J.L.B. de Aguiar, Phase change materials and energy efficiency of buildings: A review of knowledge. Journal of Energy Storage, 2020. **27**: p. 101083.

[19]. Kośny, J., PCM-enhanced building components: an application of phase change materials in building envelopes and internal structures. 2015: Springer.

[20]. Zhang, N., et al., Latent heat thermal energy storage systems with solid–liquid phase change materials: a review. Advanced Engineering Materials, 2018. **20**(6): p. 1700753.

[21].Soibam, J., Numerical Investigation of a heat exchanger using phase change materials (PCMs), in NTNU: Trondheim, Norway. 2017.

[22]. Shukla, A., A. Sharma, and P.H. Biwolé, Latent Heat-Based Thermal Energy Storage Systems: Materials, Applications, and the Energy Market. 2020: CRC Press.

[23].Christina V. Podara, Ioannis A. Kartsonakis * and Costas A. Charitidis ,Towards Phase Change Materials for Thermal Energy Storage . applied scince.

[24].Al-Absi, Z.A., M.H. Mohd Isa, and M. Ismail, Phase change materials (PCMs) and their optimum position in building walls. Sustainability, 2020. **12**(4): p. 1294.

[25].Cabeza, L.F., Advances in thermal energy storage systems. 2021: Elsevier.

[26].Frigione, M., M. Lettieri, and A. Sarcinella, Phase change materials for energy efficiency in buildings and their use in mortars. Materials, 2019. **12**(8): p. 1260.

[27].Trisnadewi, T. and N. Putra. Phase change material (PCM) with shaped stabilized method for thermal energy storage: A review. in AIP Conference Proceedings. 2020. AIP Publishing.

[28].Cárdenas-Ramírez, C., F. Jaramillo, and M. Gómez, Systematic review of encapsulation and shape-stabilization of phase change materials. Journal of Energy Storage, 2020. **30**: p. 101495.

[29].Al-Yasiri, Q. and M. Szabó, Incorporation of phase change materials into building envelope for thermal comfort and energy saving: A comprehensive analysis. Journal of Building engineering, 2021. **36**: p. 102122.

[30].Al-Yasiri, Q.M. and M. Szabó, Performance assessment of phase change materials integrated with building envelope for heating application in cold locations. European Journal of Energy Research, 2021. **1**(1): p. 7-14.

[31].Pacheco-Torgal, F., et al., Cost-effective energy efficient building retrofitting: materials, technologies, optimization and case studies. 2017: Woodhead publishing.

[32].Jia, J., et al., Energy saving performance optimization and regional adaptability of prefabricated buildings with PCM in different climates. Case Studies in Thermal Engineering, 2021. 26: p. 101164.

[33].Al-Yasiri, Q., et al., Building envelope-enhanced phase change material and night ventilation: Effect of window orientation and window-to-wall ratio on indoor temperature. Renewable Energy, 2023. 218: p. 119263.

[34].Parasonis, J., A. Keizikas, and D. Kalibatiene, The relationship between the shape of a building and its energy performance. Architectural Engineering and Design Management, 2012. 8(4): p. 246-256.

[35].Building Orientation. [cited accessed 2024; Available from:.

[36].جورج, ر. and م. ياسين, مقارنة استخدام كل من مادة متغيرة الطور (PCM) ومادة عازلة لتحسين الأداء الحراري للأبنية. Tishreen University Journal-Engineering Sciences Series, 2012. 34(4).

[37]. Bhamare, D.K., M.K. Rathod, and J. Banerjee, Passive cooling techniques for building and their applicability in different climatic zones—The state of art. Energy and Buildings, 2019. 198: p. 467-490.

[38].Sonnick, S., et al., Passive room conditioning using phase change materials—Demonstration of a long-term real size experiment. International Journal of Energy Research, 2020. 44(8): p. 7047-7056.

[39].Mukram, T.A. and J. Daniel, A review of novel methods and current developments of phase change materials in the building walls for cooling applications. Sustainable Energy Technologies and Assessments, 2022. **49**: p. 101709.

[40].M'hamdi, Y., K. Baba, and M. Tajayouti, Analysis of Energy Efficiency Potential of Hollow Brick Building Envelope Filled with PCM. Journal of Sustainability Research, 2023. **5**(3).

[41]. Awang, M., L. Ling, and S.S. Emamian, Advances in Civil Engineering Materials: Selected Articles from the International Conference on Architecture and Civil Engineering (ICACE2021). 2022: Springer Nature Singapore.

[42].GLASSX-PCM in windows. accessed 2024]; Available from: https://www.rubitherm.eu/en/references/glassx.

[43].Arasteh, H., W. Maref, and H.H. Saber, Energy and thermal performance analysis of PCM-incorporated glazing units combined with passive and active techniques: a review study. Energies, 2023. 16(3): p. 1058.

[44].VERGARA, P.C. Smart buildings. 2022 [cited accessed 2023; Available from: https://arquitecturayempresa.es/noticia/que-son-los-materiales-pmc-y-como-estan-revolucionando-la-construccion

[45]. Ahmed, A., et al. Experimental evaluation of passive cooling using phase change materials (PCM) for reducing overheating in public building. in E3S Web Conference: EENVIRO 2017 Workshop-Advances in Heat and Transfer in Built Environment. 2018. EDP Sciences.

[46]. Products, P. John Laing Coventry-UK- Passive Cooling. [cited accessed 2023; Available from: https://www.pcmproducts.net/files/John%20Laing%20Coventry-UK-%20Passive%20Cooling.pdf.

[47]. pcmproducts. TubeICE Catalogue. [cited accessed 2023; Available from: https://www.pcmproducts.net/files/thermal_storage_catalogue.pdf.

[48]. Phase-Change-Solutions. Miramar Bank. Available from: https://phasechange.com/wp-content/uploads/2022/11/ENRG-Blanket-Bank-Case-Miramar-Florida-v5.pdf.

[49]. Phase-Change-Solutions. Product Brochure ENRG Blanket®. 2022 [cited accessed 2023; Available from: https://phasechange.com/wp-content/uploads/2024/04/PCS_ENRGBlanket_Brochure.pdf.

[50]. samac.co.za. Phase Change Material in a New Construction Training Center. 2017 [cited accessed 2023; Available from: https://samac.co.za/wp-content/uploads/2018/06/ETCC-Easton-Archery-Center-report-Nov-2017.pdf.

[51]. Li, Y., et al., Effect of design parameters on thermal performance of integrated phase change material blind system for double skin façade buildings. International Journal of Low-Carbon Technologies, 2019. **14**(2): p. 286-293.

[52]. Li, Y., et al., Phase change material blind system for double skin façade integration: System development and thermal performance evaluation. Applied Energy, 2019. **252**: p. 113376.

[53]. Insolcorp. university of Maryland Medical Center [UMMC]. 2020 [cited accessed 2023; Available from: https://insolcorp.com/middle-school-new-hampshire-usa/.

[54]. Figueiredo, A., et al., Indoor thermal comfort assessment using different constructive solutions incorporating PCM. Applied Energy, 2017. **208**: p. 1208-1221.

[55]. Phase-Change-Energy-Solutions. BioPCMs M182/Q23 [cited accessed 2024; Available from: https://phasechange.com/wp-content/uploads/2020/08/BioPCM-Data-Sheet-Q23.pdf.